



Using a Plane-Wave Signal Model to Suppress Clutter and Calibrate the Array

SCHISM

(Signal and Clutter as Highly Independent Structured Modes)

Dr. George R. Legters
SAIC, Satellite Beach, FL
legtersg@saic.com
(321)777-0061



GMTI Clutter: Devastating Interference or ... Fortuitous Calibration Signal



- Many radar systems detect targets which are not buried in clutter and interference. The usual game is to **find signals in receiver noise**.
 - Because airborne GMTI radar systems are pointed at the earth, target signals are buried in enormous, **highly-structured ground clutter** return signals. **Measurement biases** also afflict airborne GMTI radar systems.
 - Playing the usual game, adaptive filters based on 2nd-order statistics must whiten colored, nonstationary clutter “noise”. Measurement biases smear and/or modulate sample covariance matrices. Performance suffers.
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- Most of the signal sampled by airborne GMTI radars comes from **near-ideal EM plane-waves**. Measurement biases are largely deterministic.
 - So the game has changed. We need to **find small target sinusoids buried in large clutter sinusoids** distorted by deterministic biases.
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- Abstract Goal: Remove the **deterministic** interference and biases **before** they mangle the second-order statistics.

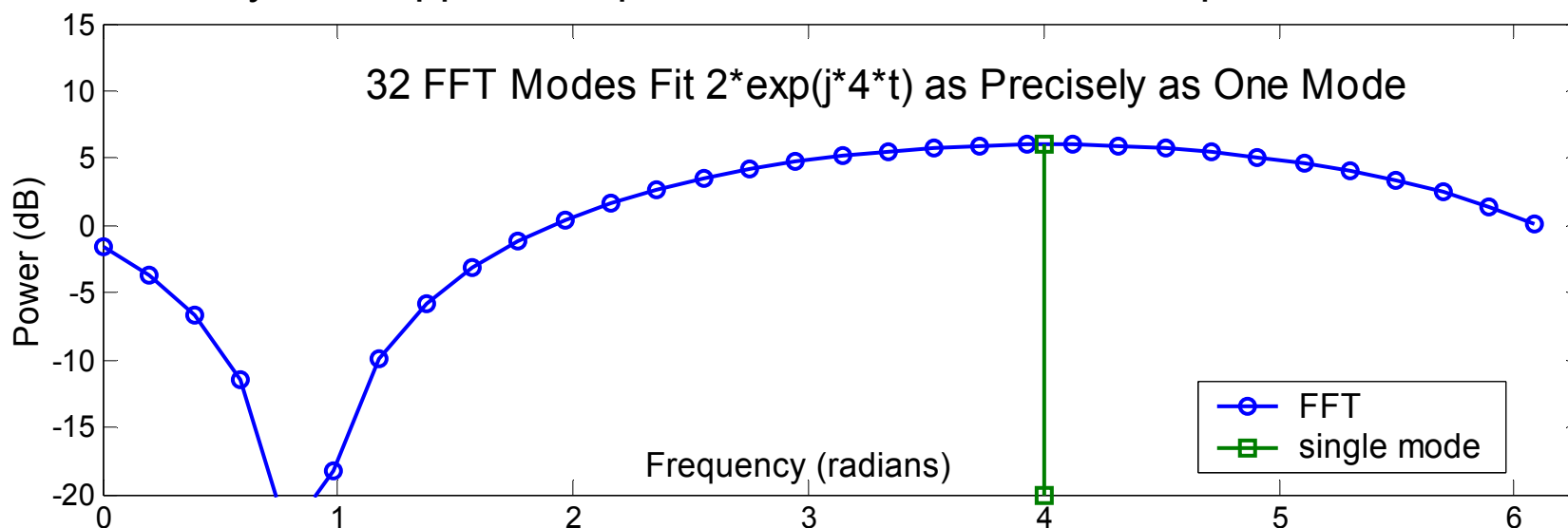


Fanatical Exploitation of One Piece of Prior Information (One-Note KASSPER)



- **Prior Information: Radar return signal is a superposition of near-ideal EM plane waves, many of which possess a very high S/N.**
 - Fact: Precise frequency & amplitude estimation is possible for strong signals.
 - Consequence: Radar return can be coherently analyzed into precise clutter and signal modes (beam-Doppler plane waves; nonorthogonal over support).
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- Benefit: A deterministic, precise, coherent clutter model provides a very sharp, selective interference+jammer filter (subtract out interference).
 - Benefit: An accurate estimate of the ideal radar return signal can be synthesized for calibration-on-clutter (remove deterministic biases).
 - Benefit: Non-moving scatterers are not filtered out. The radar operates simultaneously in MTI and "SAR" modes.
 - Benefit: An accurate estimate of the clutter signal provides a reference for motion-compensation, etc. when merging CPIs.
 - Benefit: A precise estimate of the clutter modes can provide control points for registering targets to ground coordinates or for navigation.
 - Benefit: Sample covariance matrices are avoided (perhaps entirely), and the processing load promises to be lighter than MVDR STAP or multi-beam SAR.

- How many samples are required to estimate the complex amplitude and real frequency of a complex sinusoid, $s(t) = a \cdot \exp(j \cdot \omega \cdot t)$? Maybe two.
- $\omega = \text{angle}[s(2)/s(1)]$; $a = s(1) \cdot \exp(-j \cdot \omega)$ **if** Nyquist, no noise, isolated mode.
- For high S/N, very precise frequency and amplitude estimation is possible with limited sample support (ability to taper for low sidelobes doesn't hurt).
- With only two support samples, other answers are also possible.



- Limited sample support precludes a unique answer. Many answers are equivalently **precise**. For beam-Doppler clutter analysis, pretend that answers requiring the fewest modes are more **accurate** (point sources).



Analysis Algorithm Considerations



- Point target and clutter models favored over diffuse models.
 - Algorithms based on mode orthogonality do not match the model.
 - True 2D algorithms exhibit better S/N and (nonorthogonal) mode isolation.
 - Modes are most concentrated in the beam-Doppler frequency domain.
 - Data tapering can further isolate modes (sparse design matrices).
 - Performance metrics are MDV, detection and false alarm probabilities. Error power minimization is of secondary concern (unfortunately).
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- Quadratic metrics tend to evenly distribute power among modes.
 - Nonquadratic metric had capture zone limit and greatly reduced efficiency.
 - Alternating projection attempt took too many iterations to sharpen mode.
 - Prony algorithm designed for deterministic “superresolution”.
 - **Autoregressive model \Rightarrow filter with zeros at the signal mode frequencies**
 - **Zeros typically not on unit torus (precise solution is not unique).**
 - **Unknown process order and 2D model gets complicated (not Toeplitz).**
 - CLEAN-type algorithm previously produced promising results
 - Modified CLEAN algorithm perturbs frequencies to minimize error.



Modeling Plane-Wave Modes using (a GMTI Variant of) the CLEAN Algorithm



- N space and M time plane wavefront samples can be modeled as

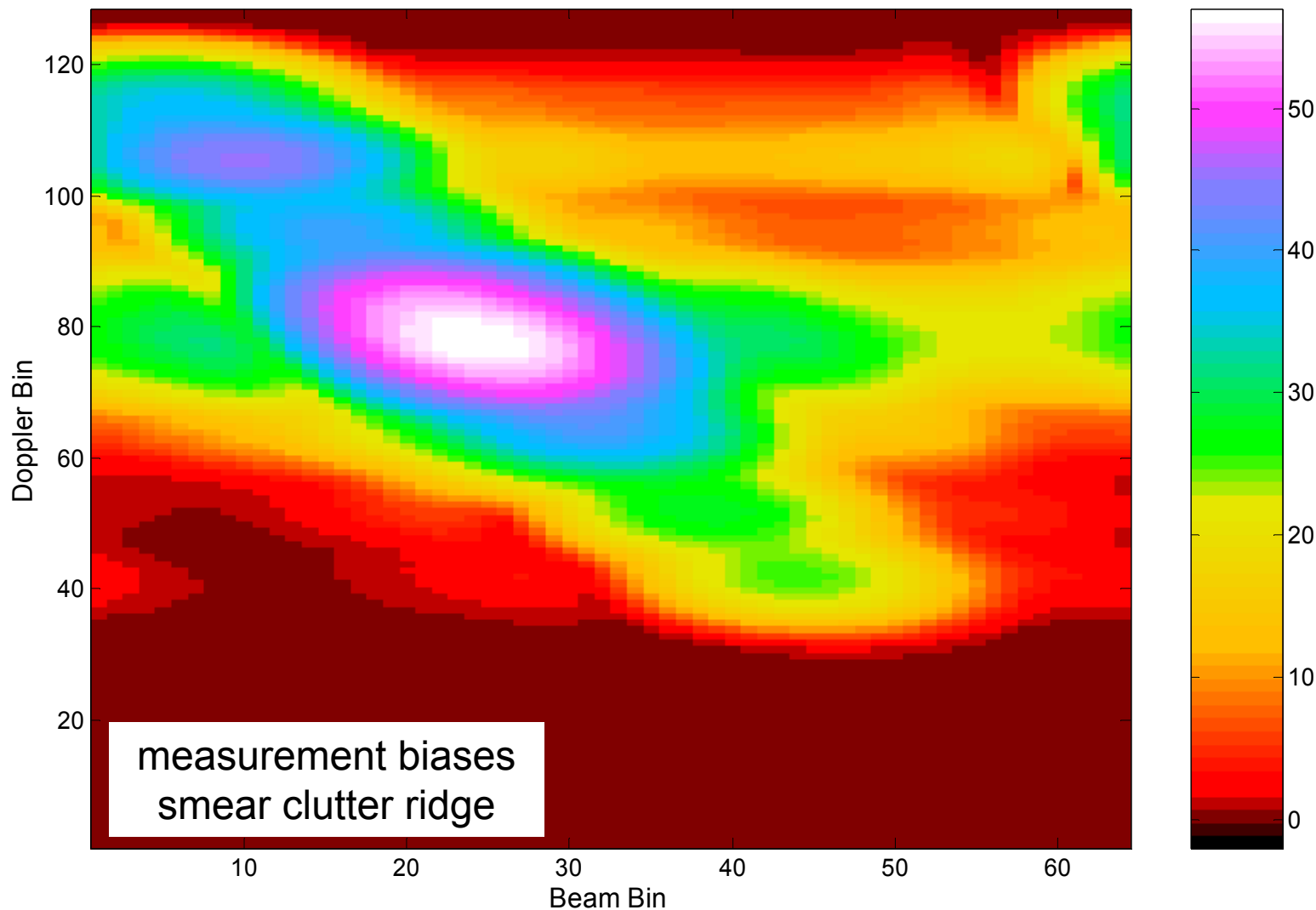
$$y_{n,m}(\mathbf{A}, \boldsymbol{\kappa}, \boldsymbol{\omega}) \equiv \sum_{p=1}^P A_p \cdot \exp[j \cdot (\boldsymbol{\kappa}_p \cdot \mathbf{n} + \omega_p \cdot m)] + v_{n,m} \quad (v \equiv \text{weak random noise})$$

complex amplitude	A_i ;	spatial frequency	$\kappa_i \equiv \frac{2 \cdot \pi}{\lambda} \cdot \sin(\theta_i) \cdot \Delta x$;	temporal frequency	$\omega_i \equiv 2 \cdot \pi \cdot f_i \cdot \Delta t$
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1. Find frequency and amplitude of largest peak in beam-Doppler FFT of data.
 2. Subtract out a fraction of the ideal response for that frequency and amplitude.
 3. Repeat until power drops below a desired threshold (e.g. noise floor + 13 dB).
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- Imprecise amplitude estimates produce spurious modes (false alarms).
 - Heavy data tapers reduce mode crosstalk, improving amplitude estimates.
 - Low loop gains reduce power of spurious modes (false alarms).
 - Precise CLEAN model splits scatterer power into many modes.
 - Transform back to space-time data domain to obtain an accurate model.

Uncalibrated Datacube Range-Averaged Beam-Doppler Power

lband-set1 Datacube Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)

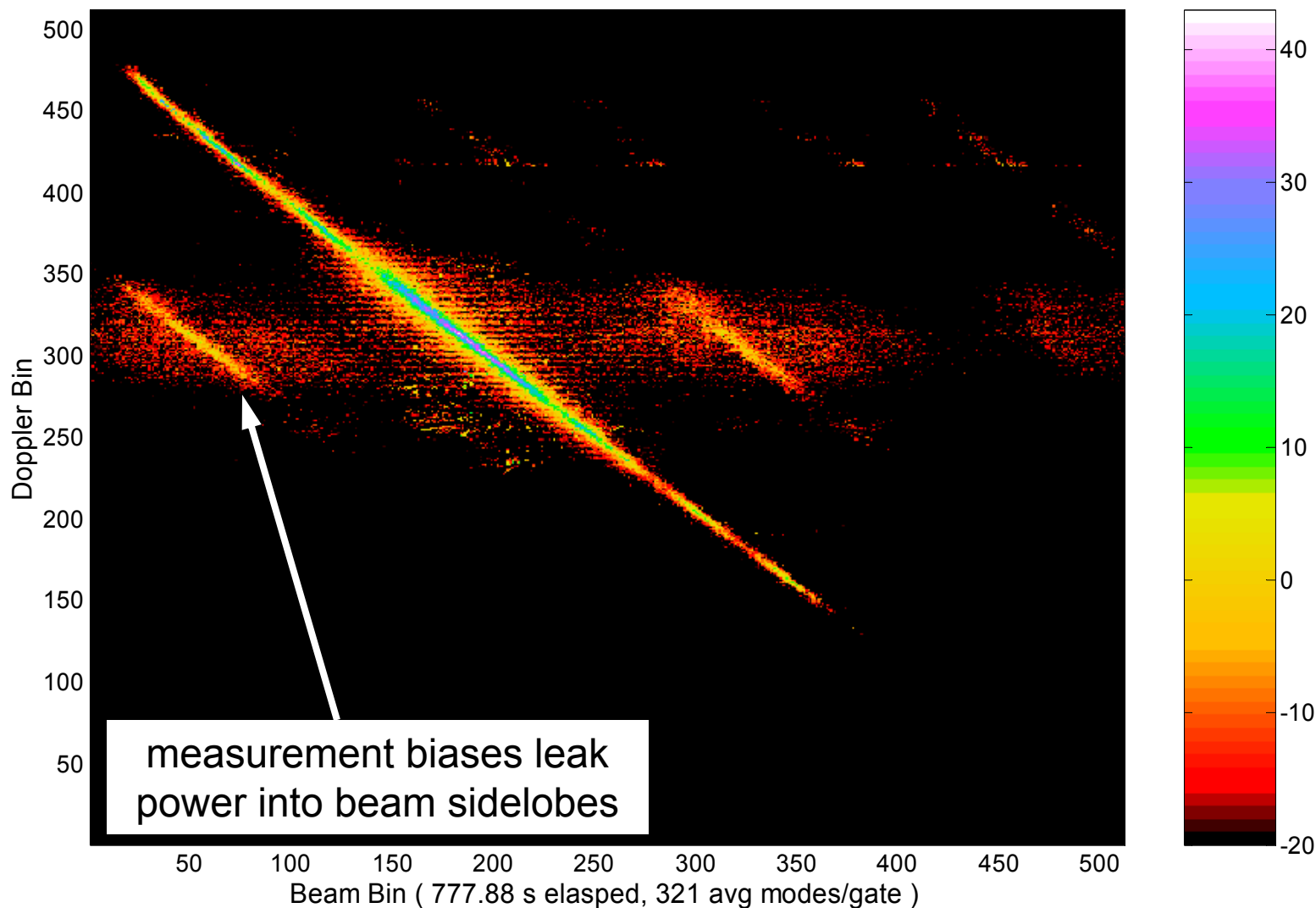




Uncalibrated SCHISM Estimate Range-Averaged “Power” (modes not orthogonal)



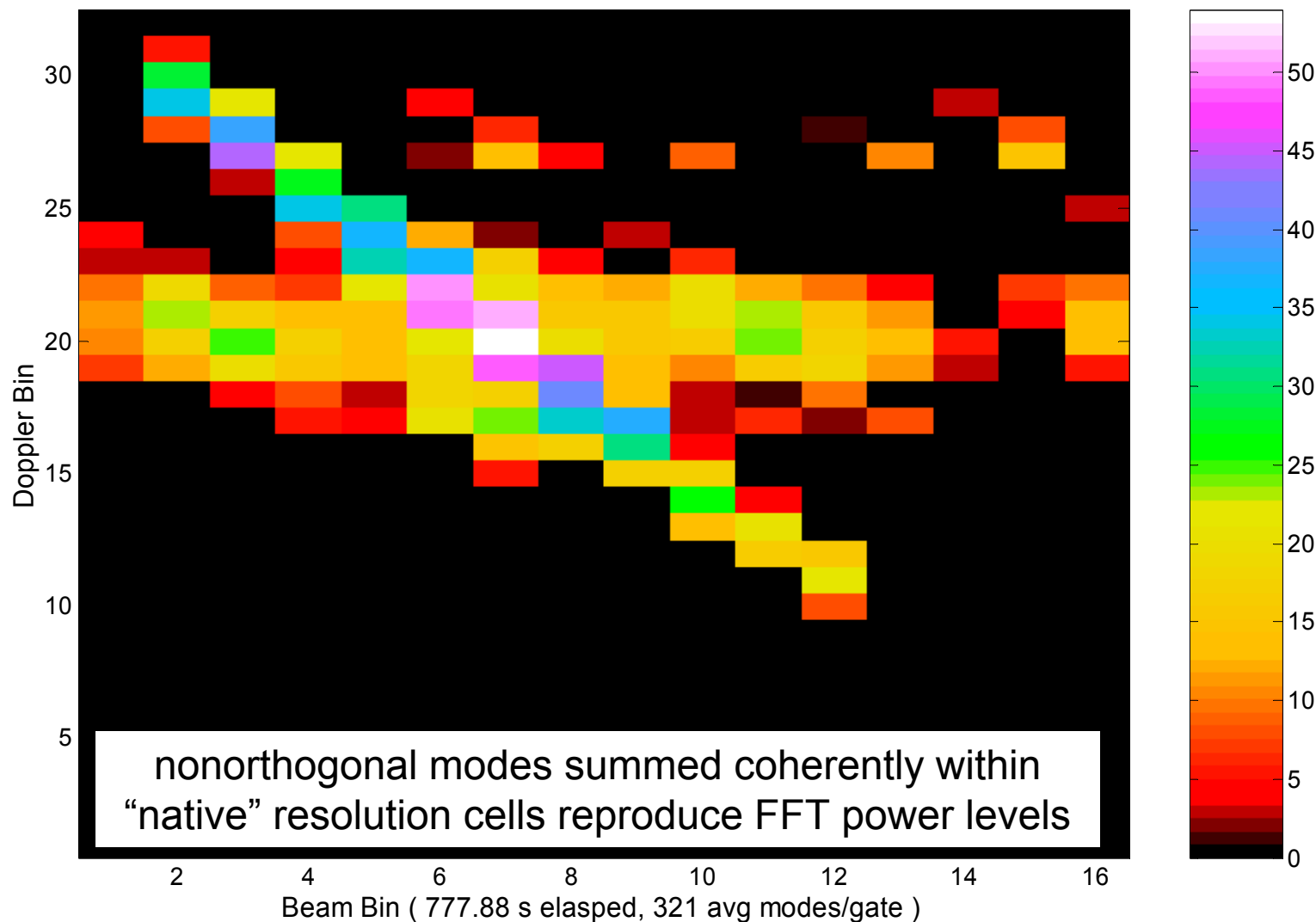
Iband-set1X-4-256 Scatterer Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)





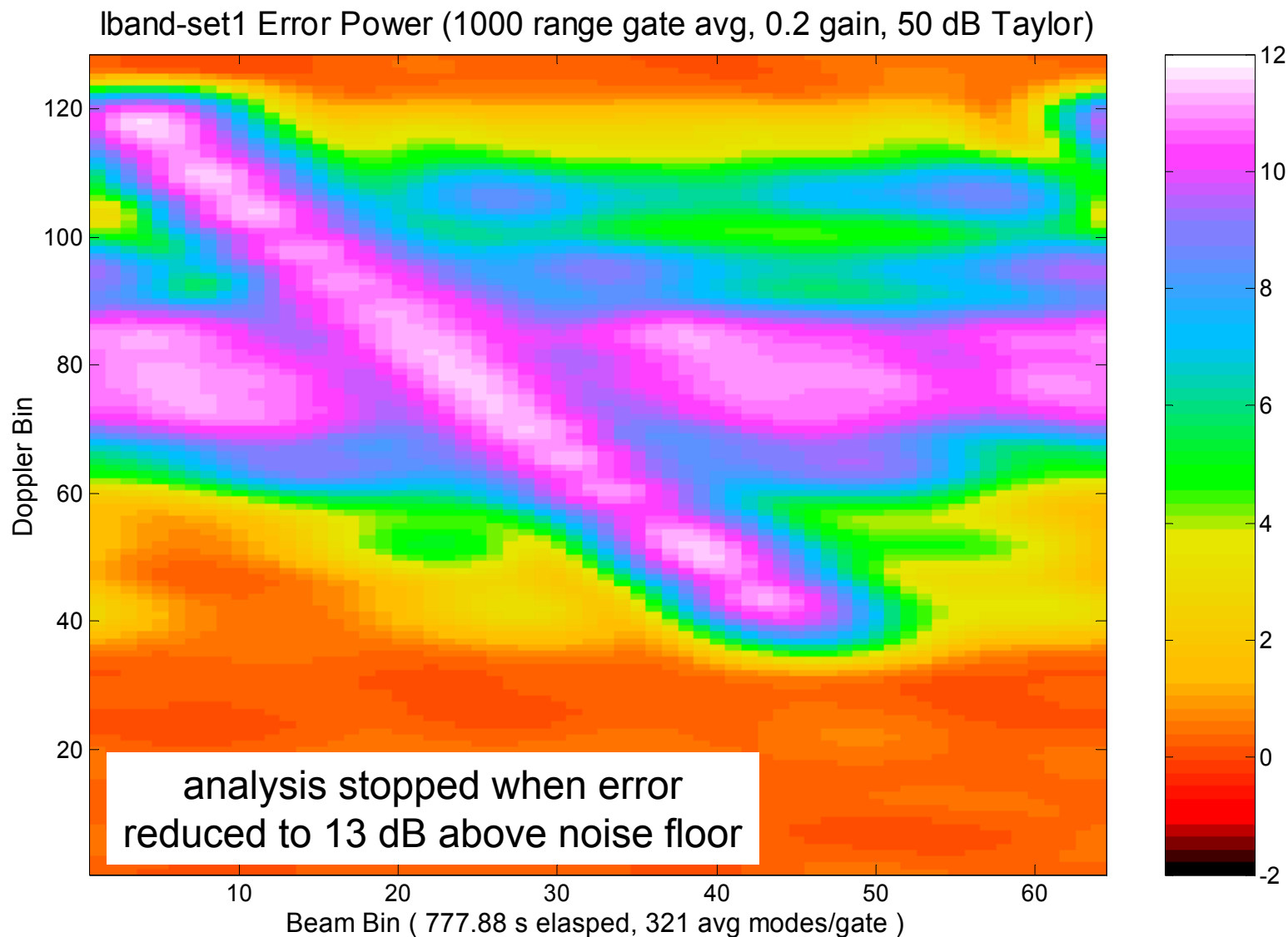
Uncalibrated SCHISM Estimate Low-Resolution Range-Averaged “Power”

lband-set1X-4-256 Scatterer Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)





Uncalibrated Range-Averaged Estimation Error Beam-Doppler Power



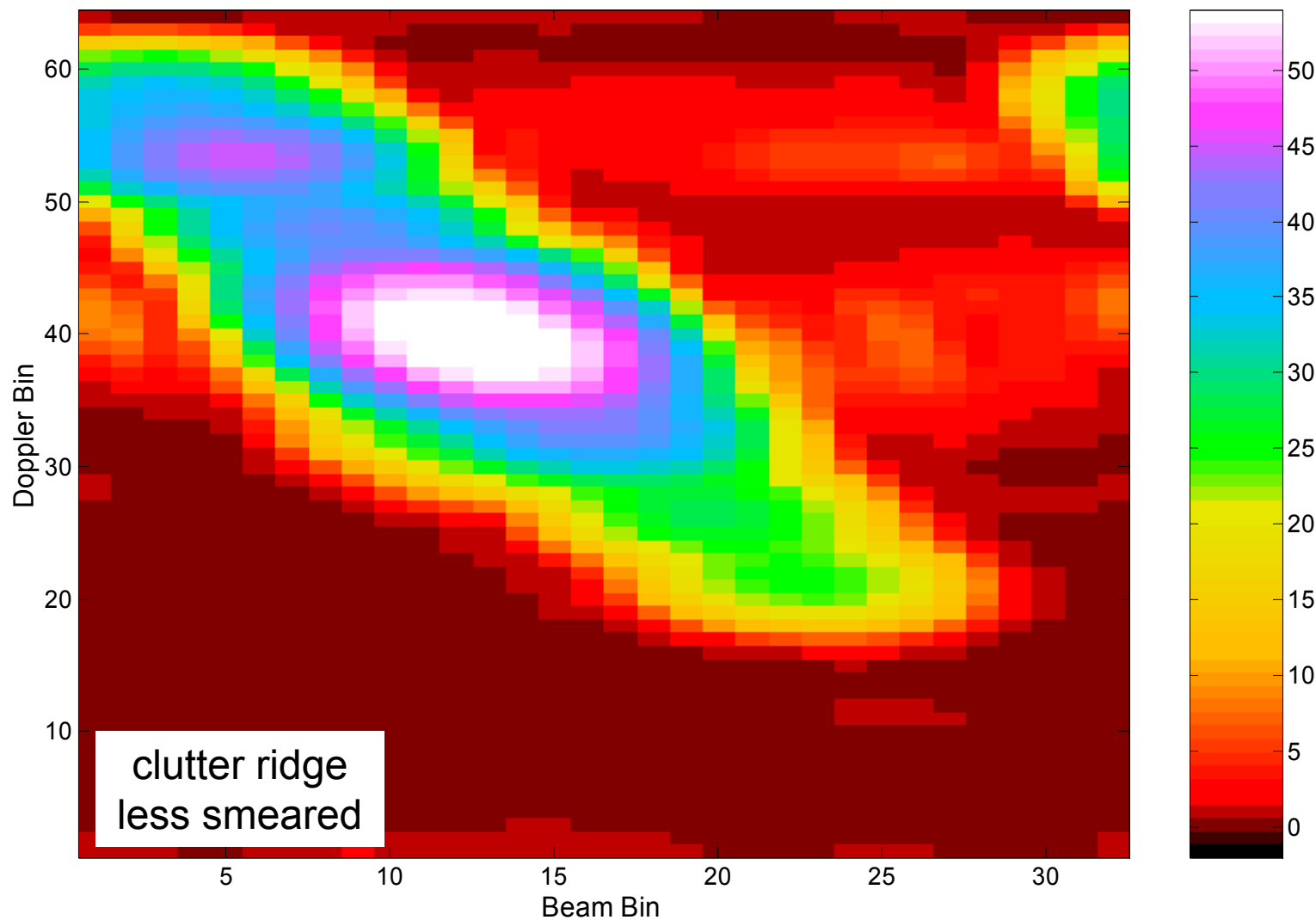
- **The goal is to focus the datacube**, so that the sample gain is uniform and the samples are uniformly-spaced in space-time.
 - SCHISM was originally developed for calibration on clutter.
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1. Fit the dominant average clutter ridge to a quadratic (\approx linear).
 2. Throw away modes off the main clutter ridge (negligible power).
 3. Transform datacube and clutter model to range-Doppler domain.
 4. Compare the Doppler phase of the ideal signal to the actual signal for all spatial elements. Correct the datacube phase.
 5. Transform back to space-time to obtain a datacube with equal element spacing and calibrated channel phase.
 6. Use average datacube channel power to equalize channel amplitudes. Do the same across time samples if necessary.
 7. More CPIs might allow element pattern calibration, etc.



Focused Datacube Range-Averaged Beam-Doppler Power

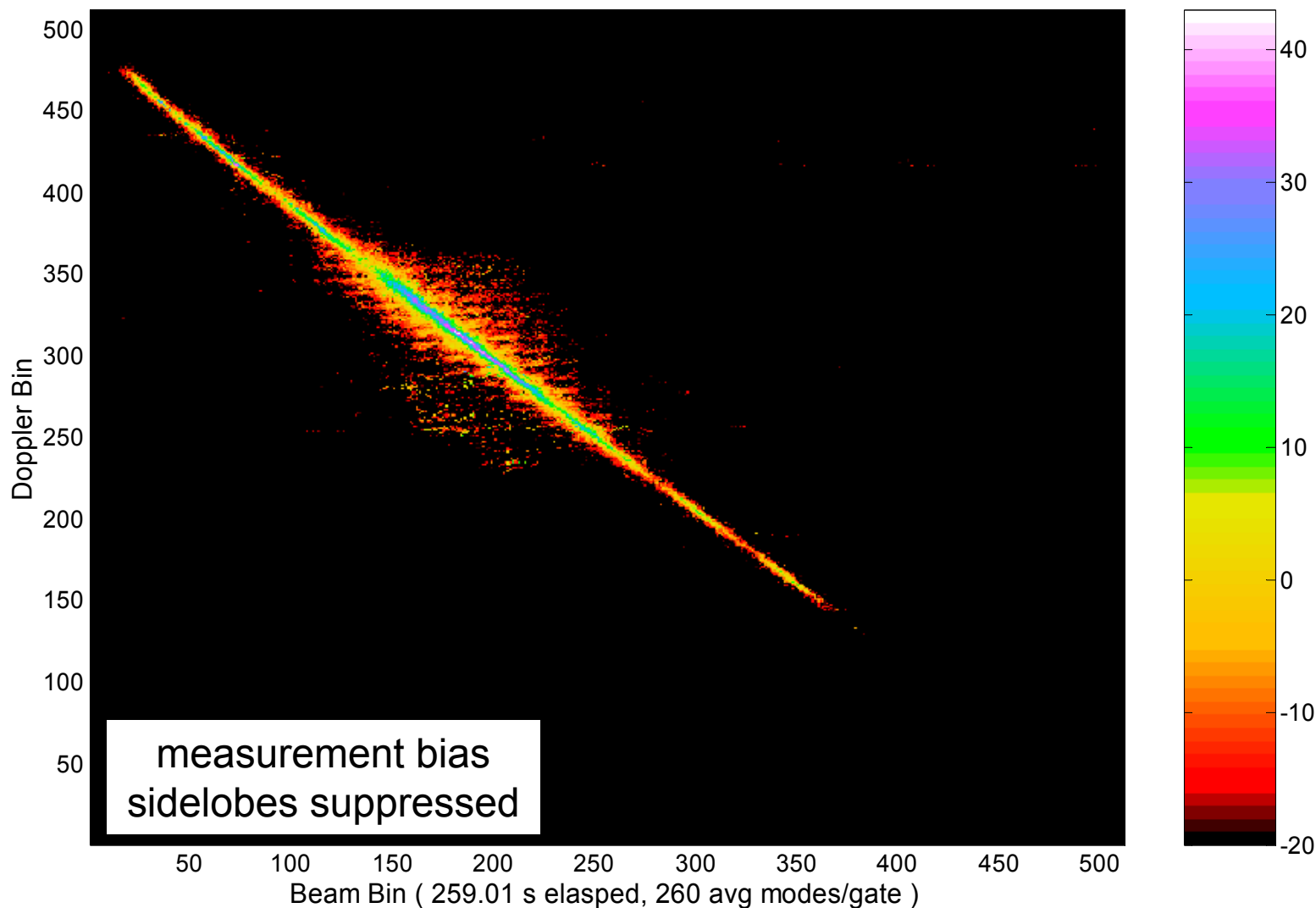


lband-set1EF Datacube Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)



Plane Wave Signal Model (Legters)

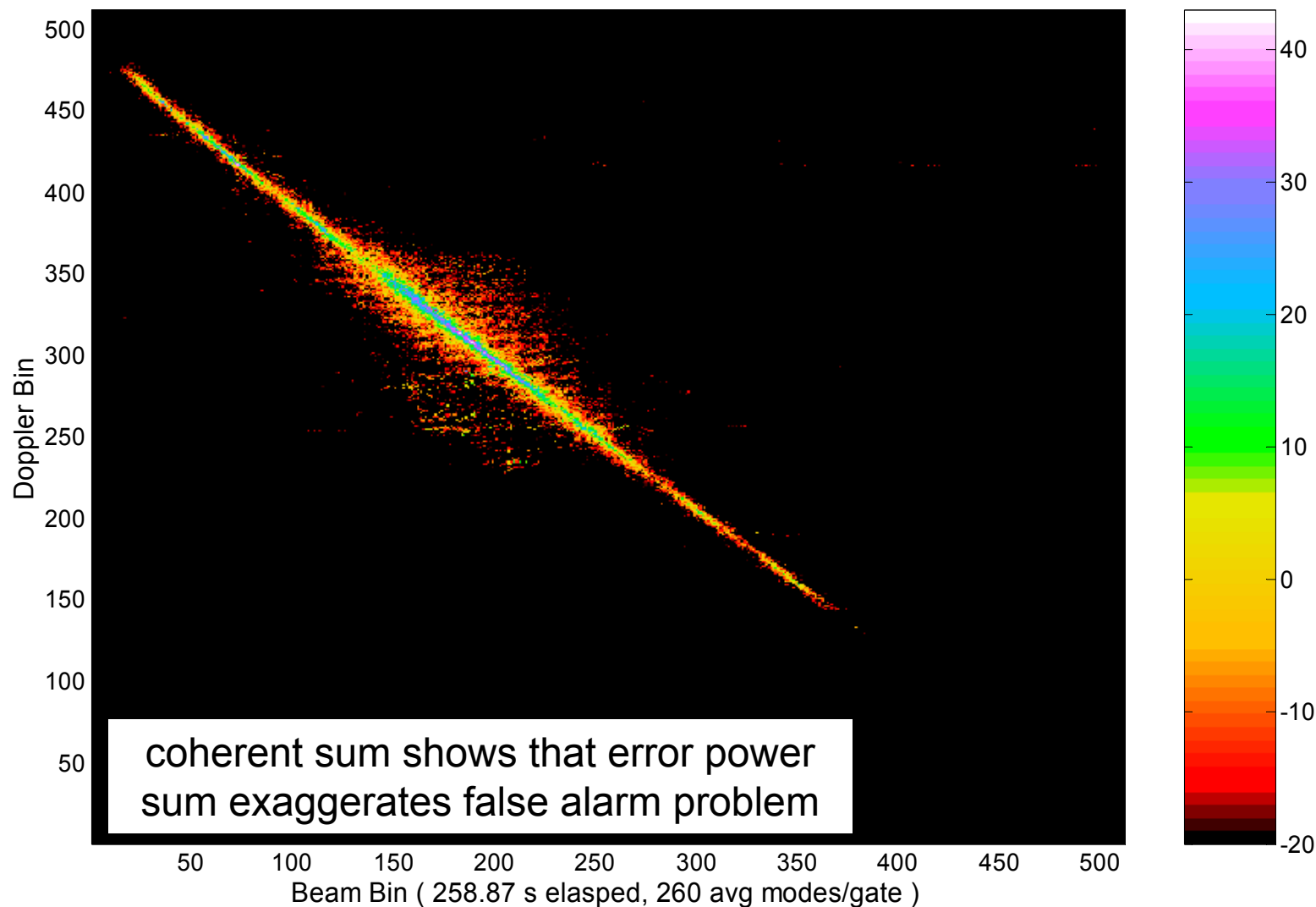
lband-set1EFX-2-256 Scatterer Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)





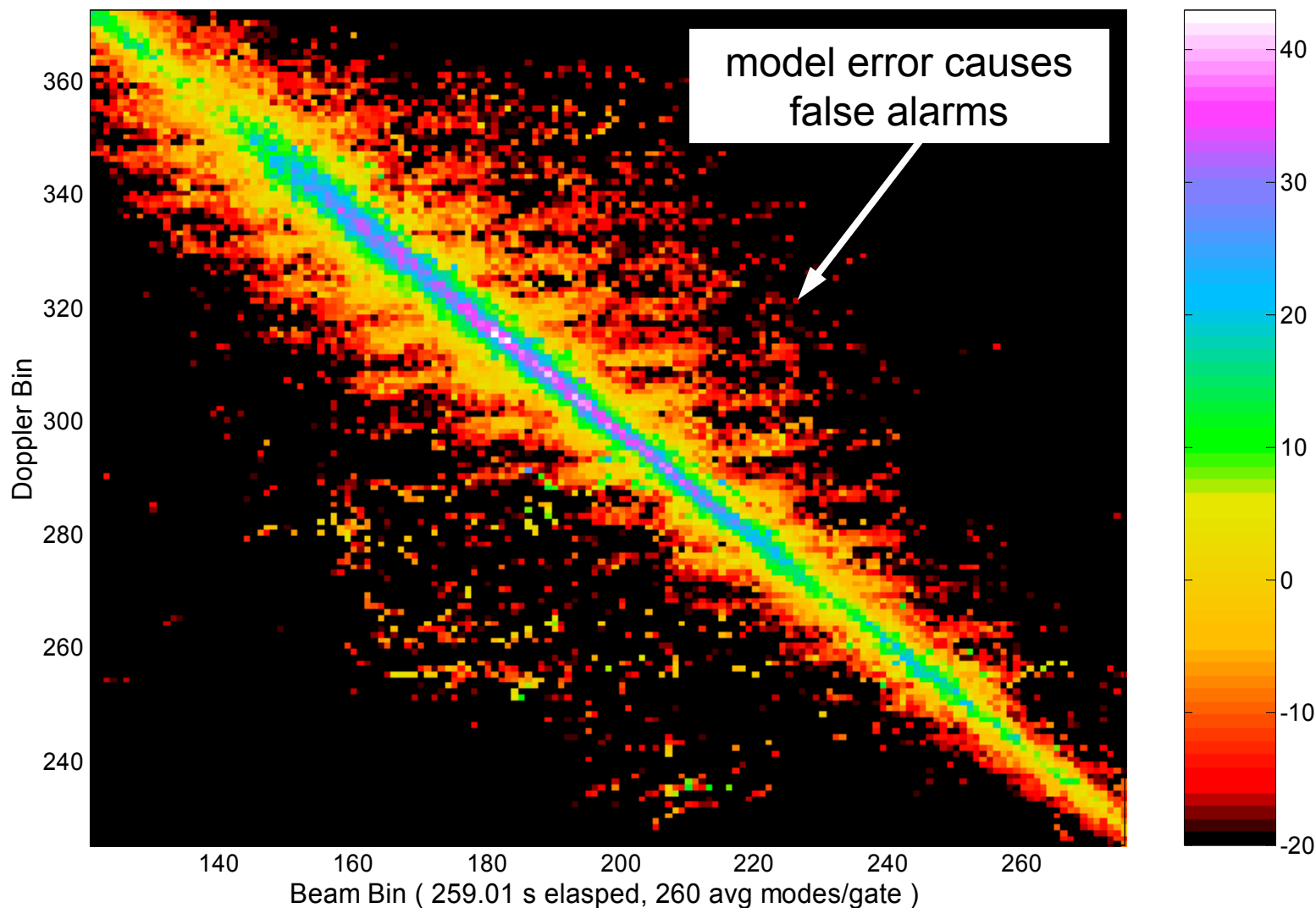
Focused SCHISM Estimate Range-Averaged Amplitudes

iband-set1EFX-2-256 Scatterer Amplitude (1000 range gate avg, 0.2 gain, 50 dB Taylor)



Focused SCHISM Estimate Range-Averaged "Power" (modes not orthogonal)

lband-set1EFX-2-256 Scatterer Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)

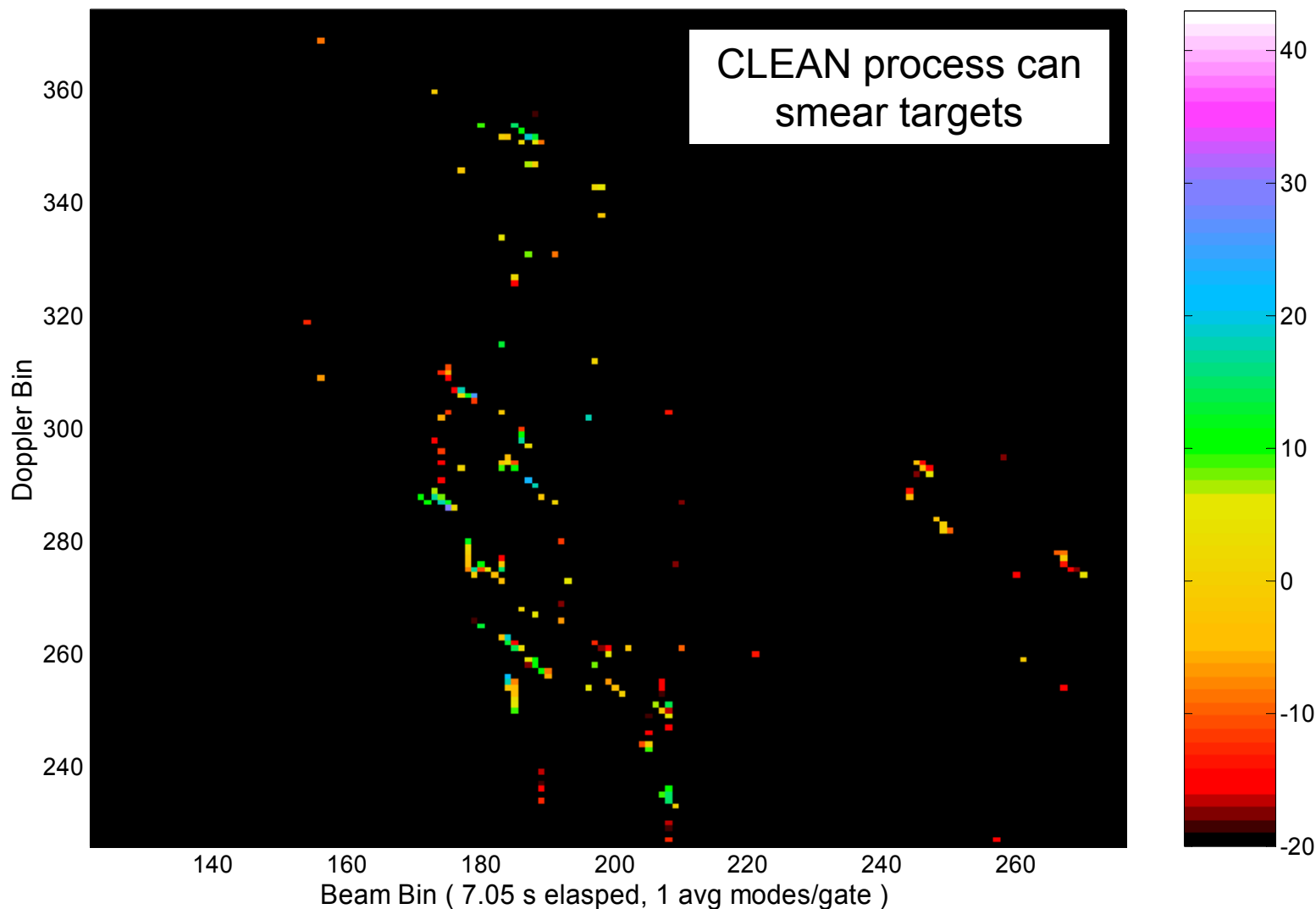


Plane Wave Signal Model (Legters)



Focused SCHISM Estimate Range-Averaged Target-Only "Power"

iband_s et1_t argEFX-2-256 Scatterer Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)

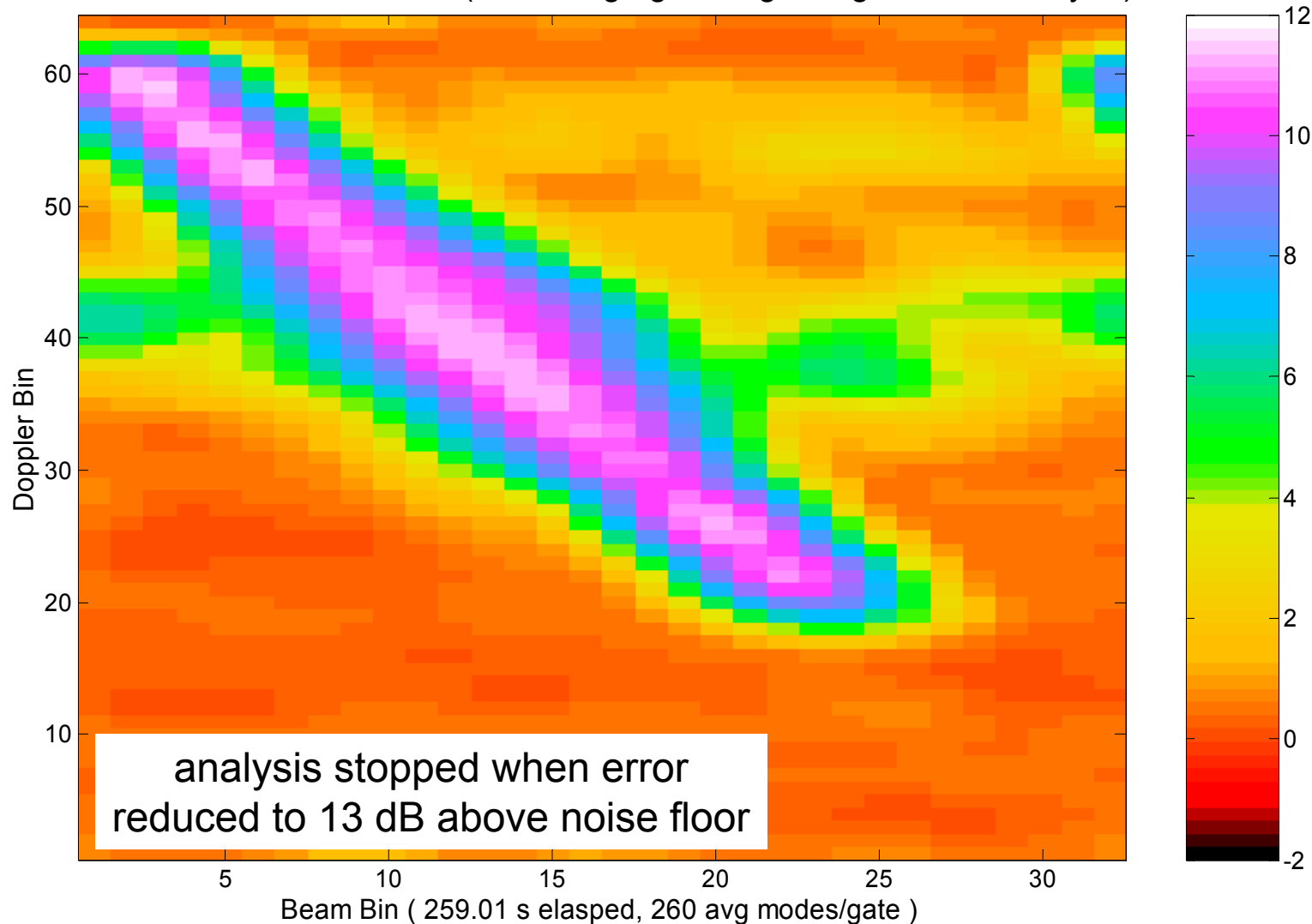




Focused Range-Averaged Estimation Error Beam-Doppler Power

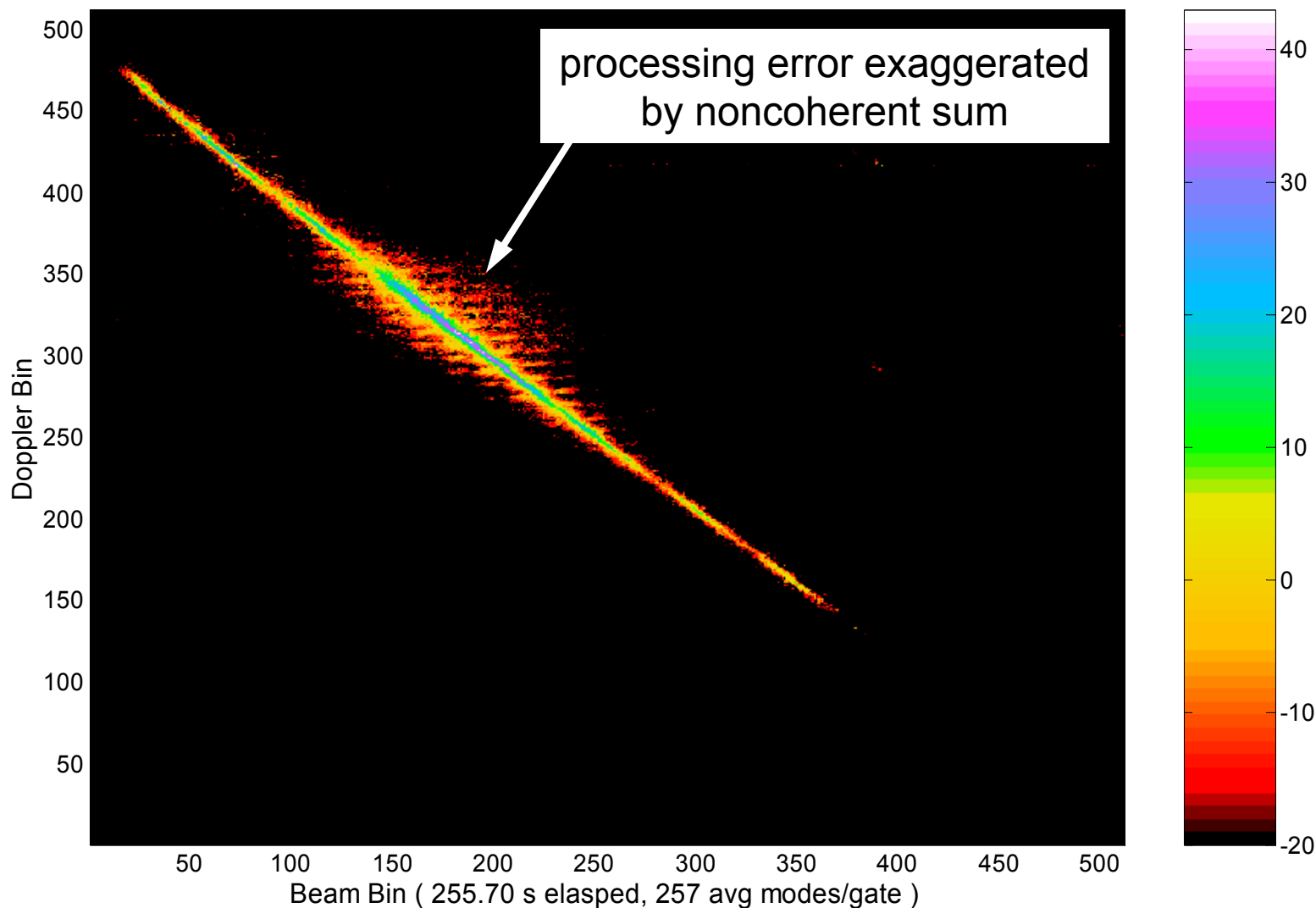


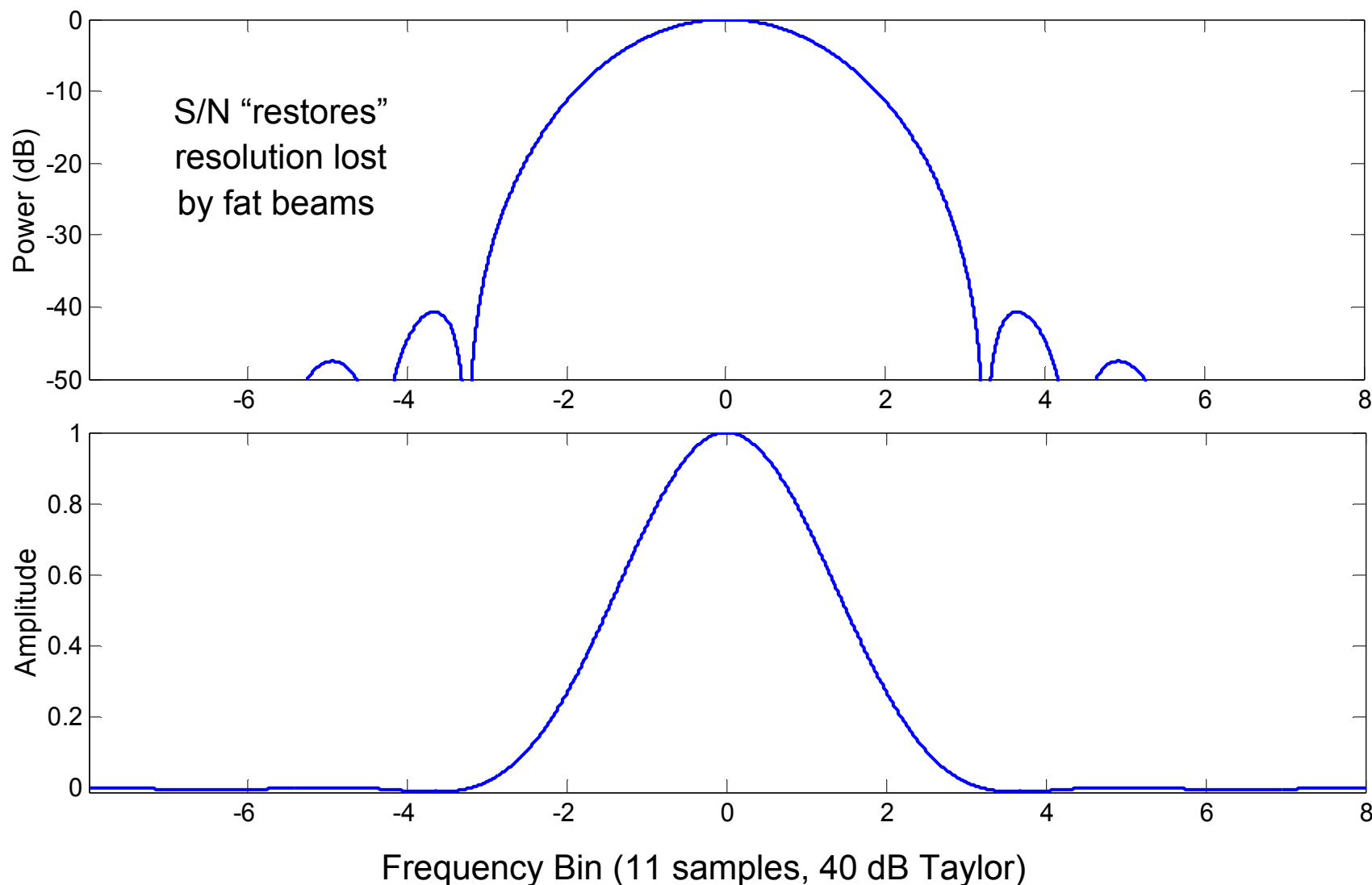
lband-set1EF Error Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)

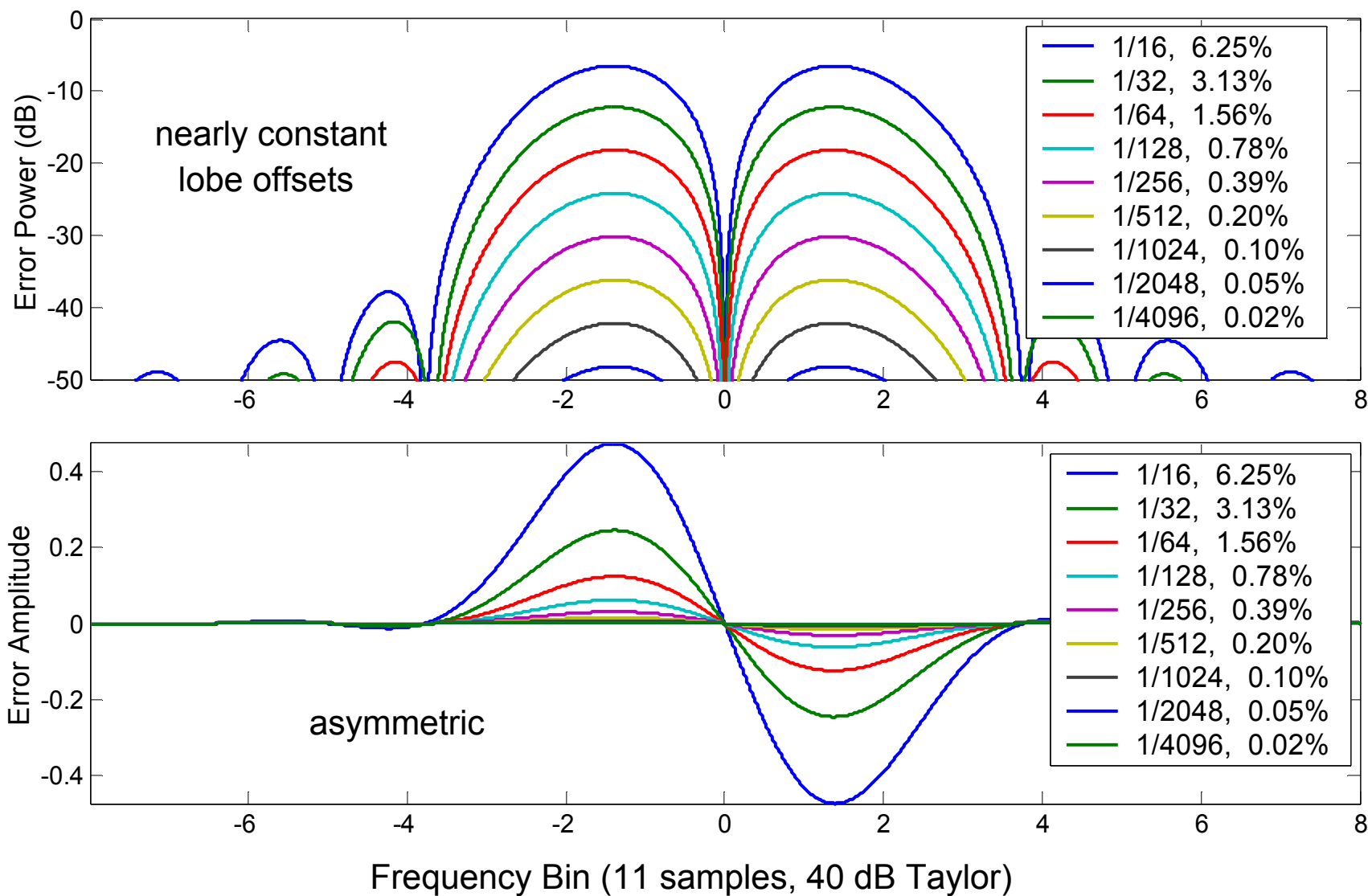


Focused SCHISM Estimate Range-Targetless Averaged "Power"

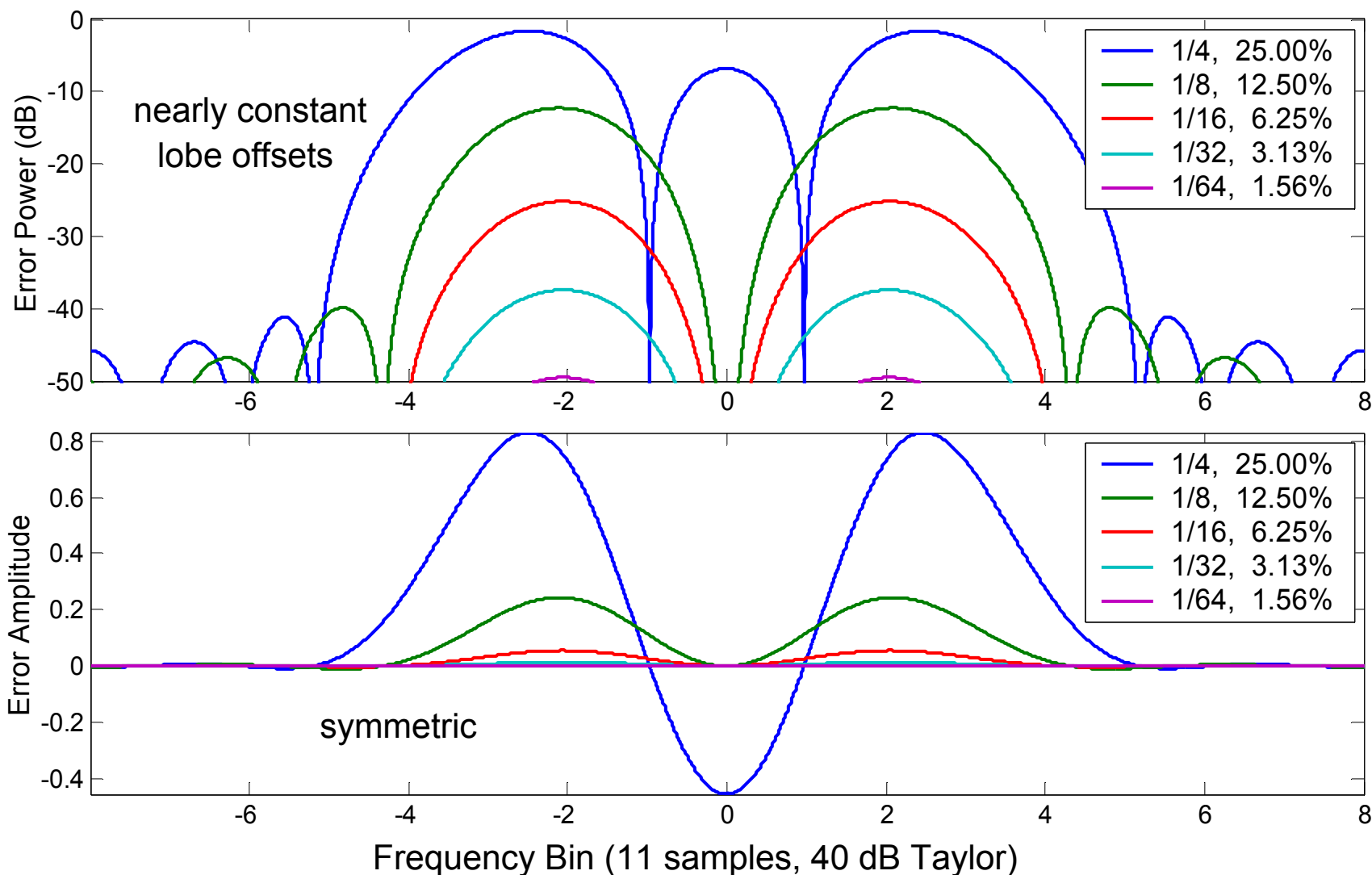
iband_s et1_n gmEFX-2-256 Scatterer Power (1000 range gate avg, 0.2 gain, 50 dB Taylor)





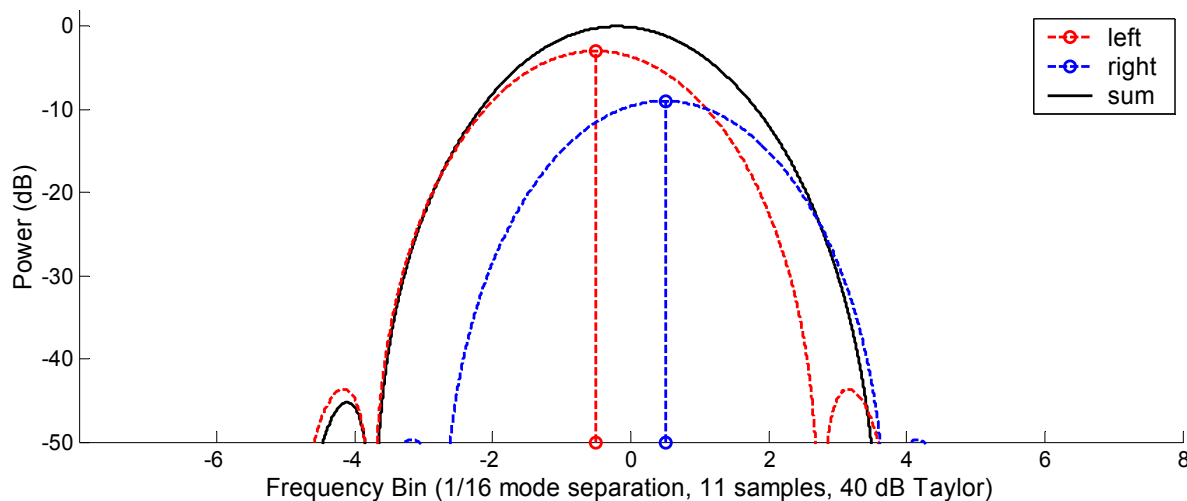


Lobe Structure for Various (Broad) Mode Pair Frequency Separations

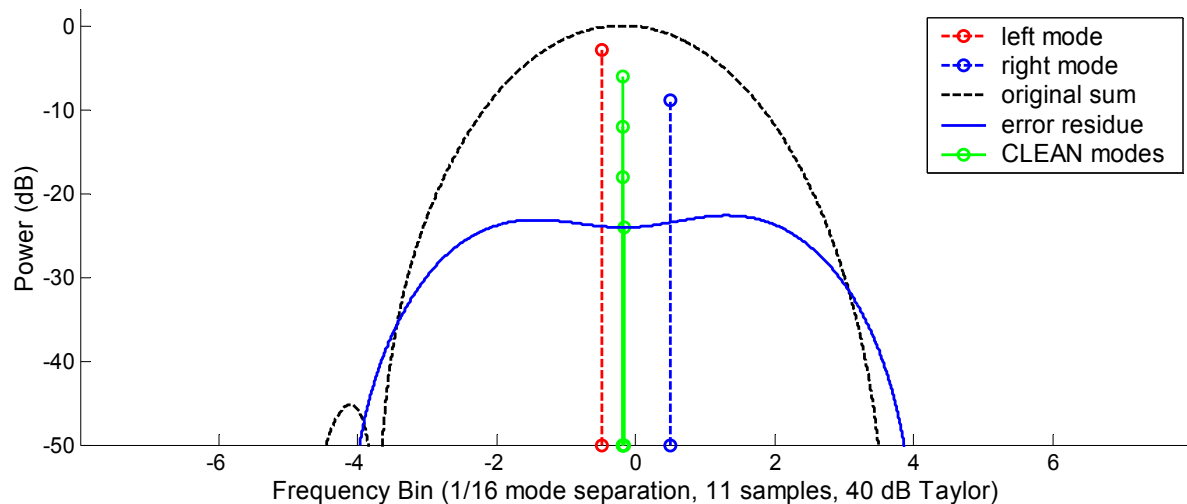


CLEAN Mode Operation and Error Sensitivity

Lobe Structure for Two In-Phase Modes

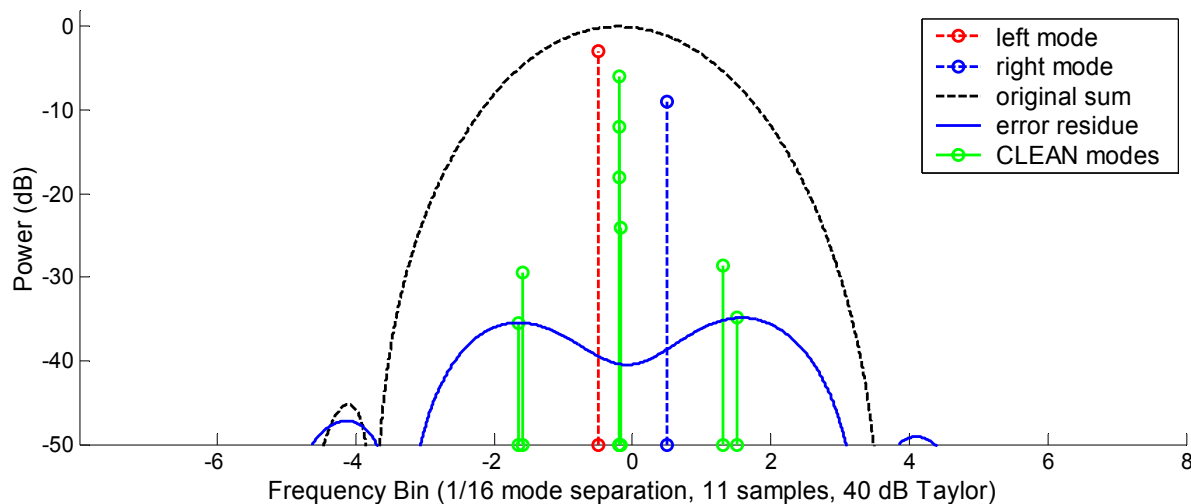


4 Pass, Gain 0.5 CLEAN (Two In-Phase Modes)

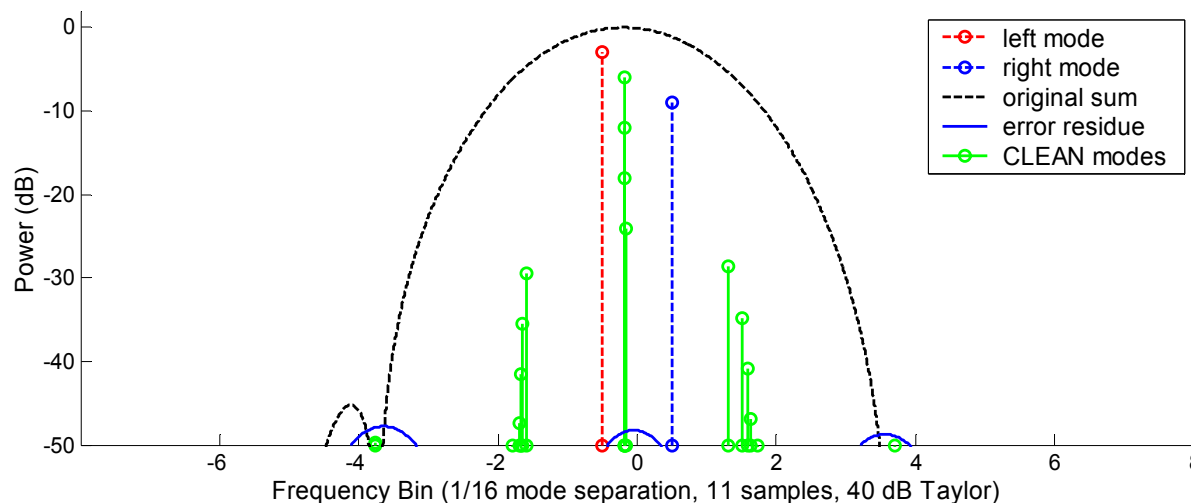


CLEAN Mode Operation and Error Sensitivity

8 Pass, Gain 0.5 CLEAN (Two In-Phase Modes)



16 Pass, Gain 0.5 CLEAN (Two In-Phase Modes)



- N space and M time plane wavefront samples can be modeled as

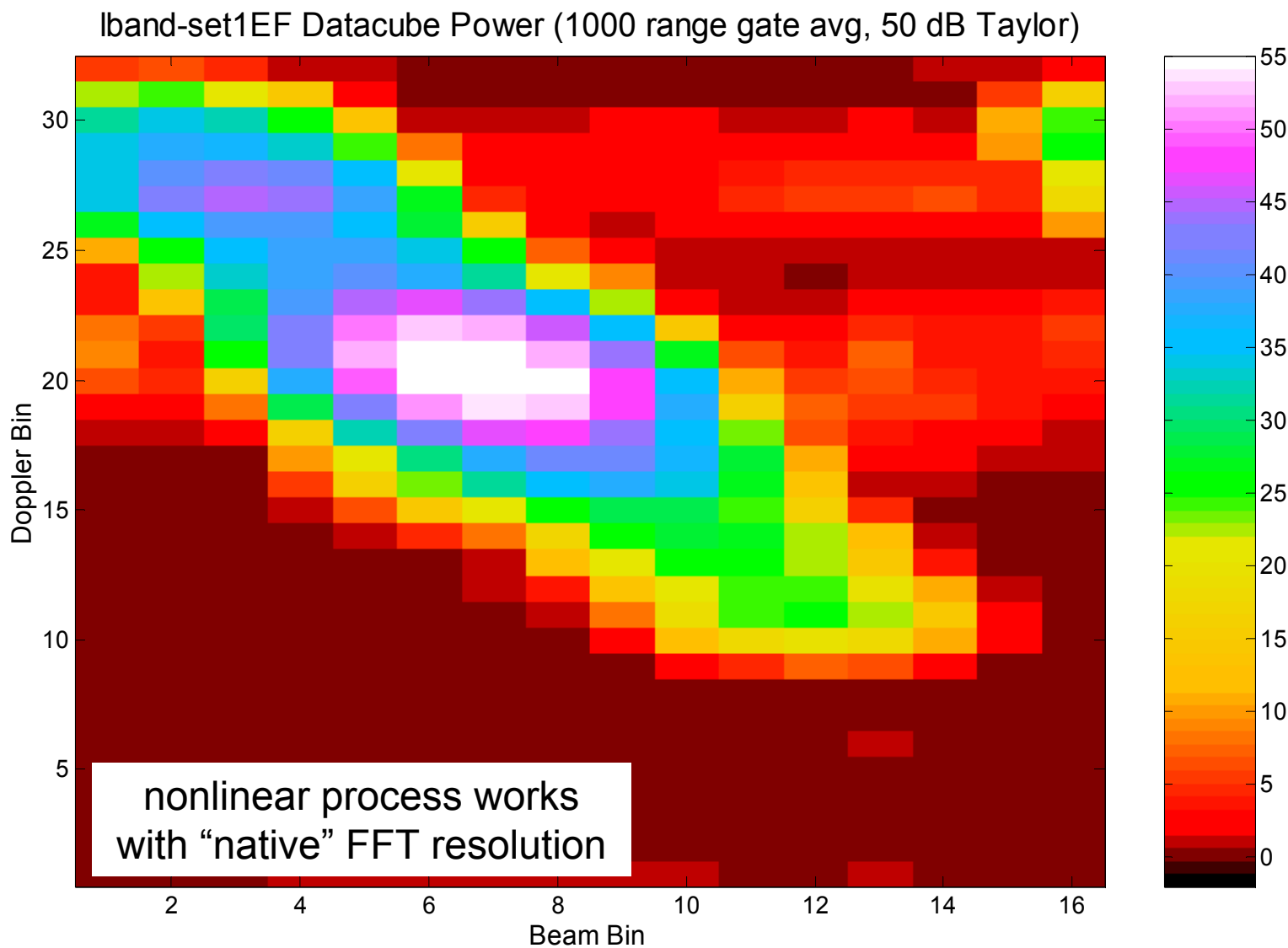
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1. Find and include frequency of largest peak of beam-Doppler data FFT.
 2. Solve for (all) mode amplitudes which most closely fit FFT of data.
 3. Perturb frequencies and again solve for amplitudes.
 4. Retain frequency perturbations which reduce modeling error.
 5. Repeat until power drops below a desired threshold (e.g. noise floor + 13 dB).
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- Brute force approach takes more time (working on more efficient techniques).
 - Drastically fewer modes than CLEAN (17 versus 260 average per range bin).
 - Tricky business (error modes can be linear combination of regular modes).



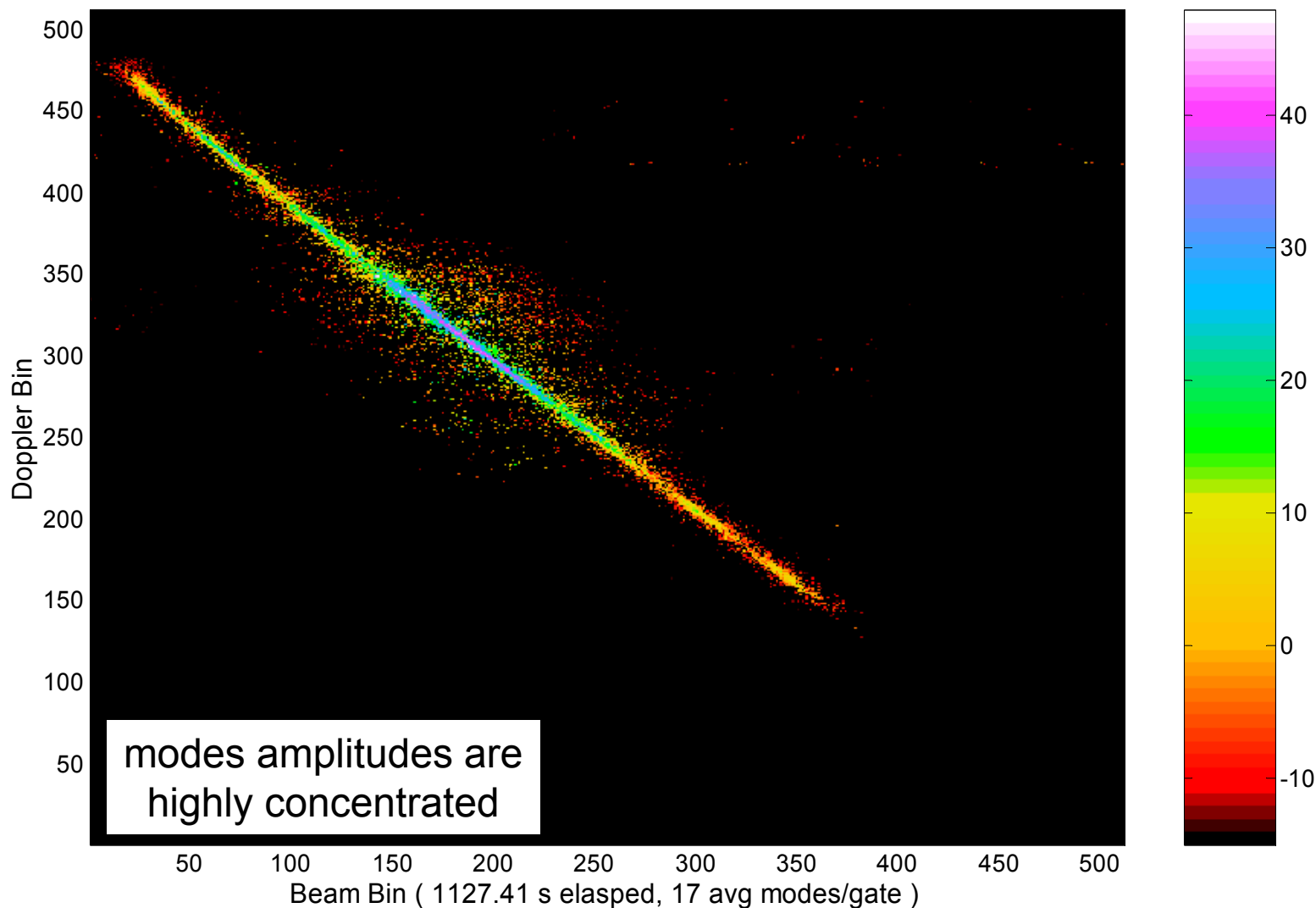
Focused Datacube Range-Averaged Beam-Doppler Power





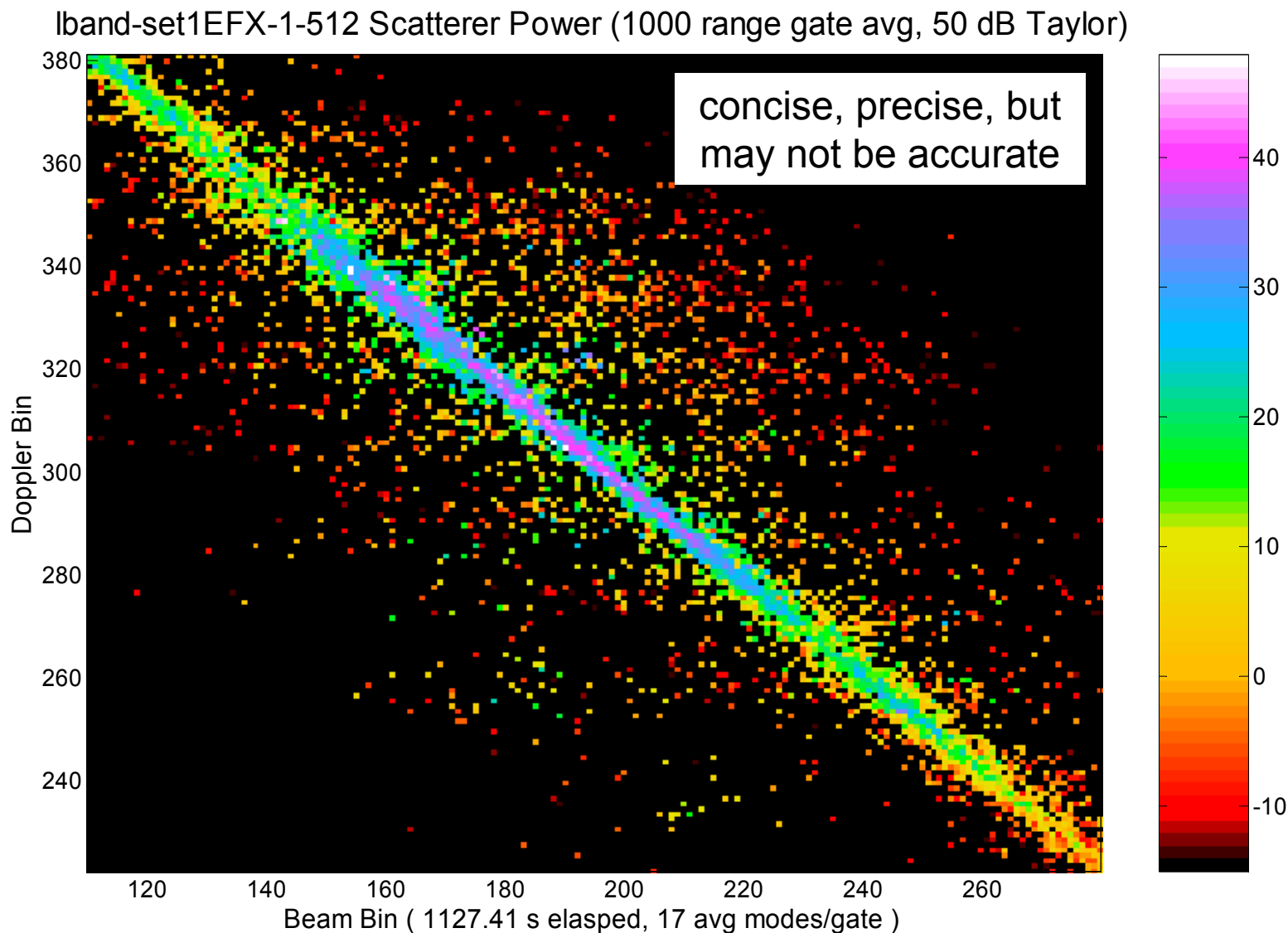
Focused Nonlinear Estimate Range-Averaged "Power" (modes not orthogonal)

lband-set1EFX-1-512 Scatterer Power (1000 range gate avg, 50 dB Taylor)



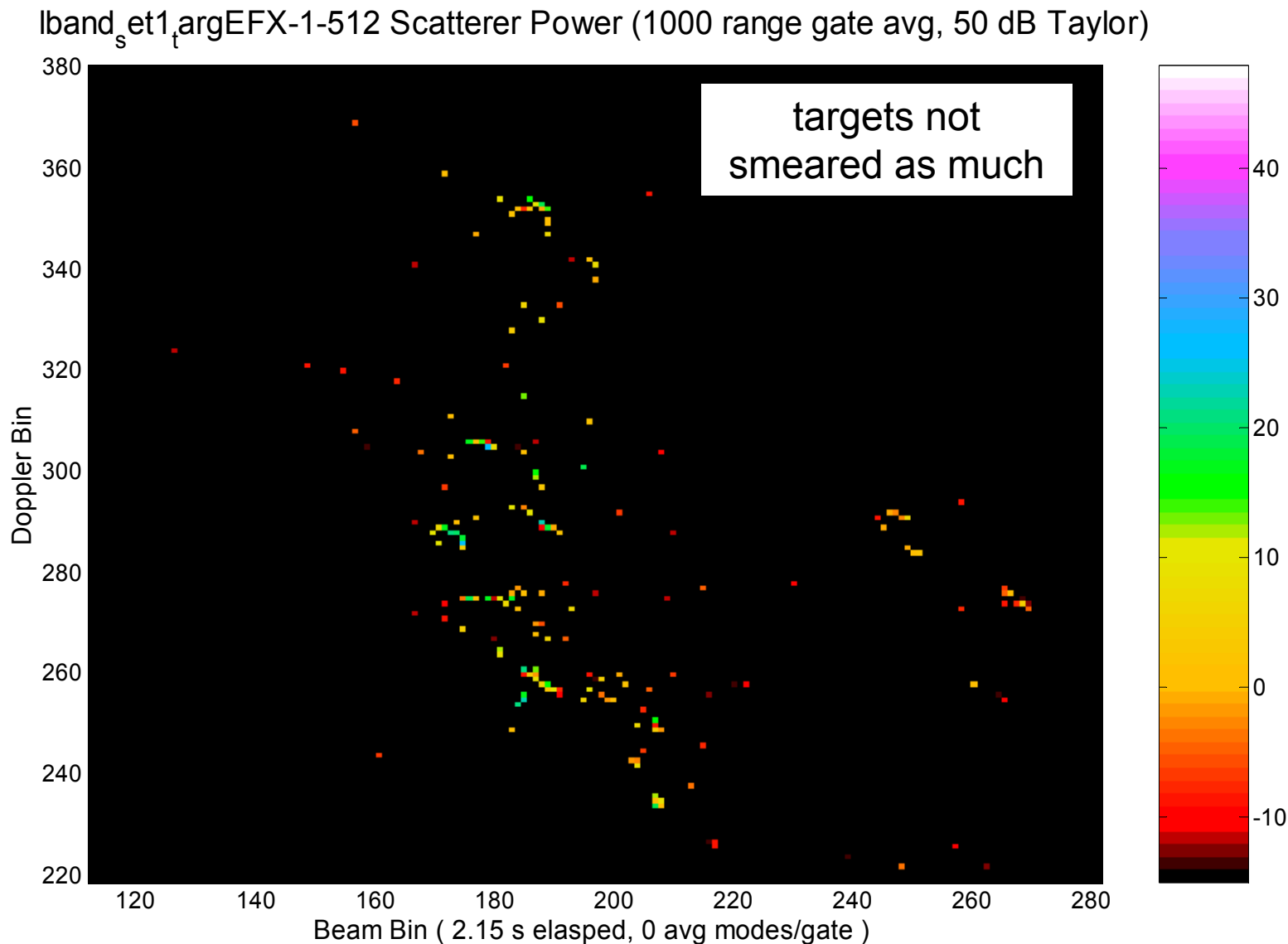


Focused Nonlinear Estimate Range-Averaged "Power" (modes not orthogonal)

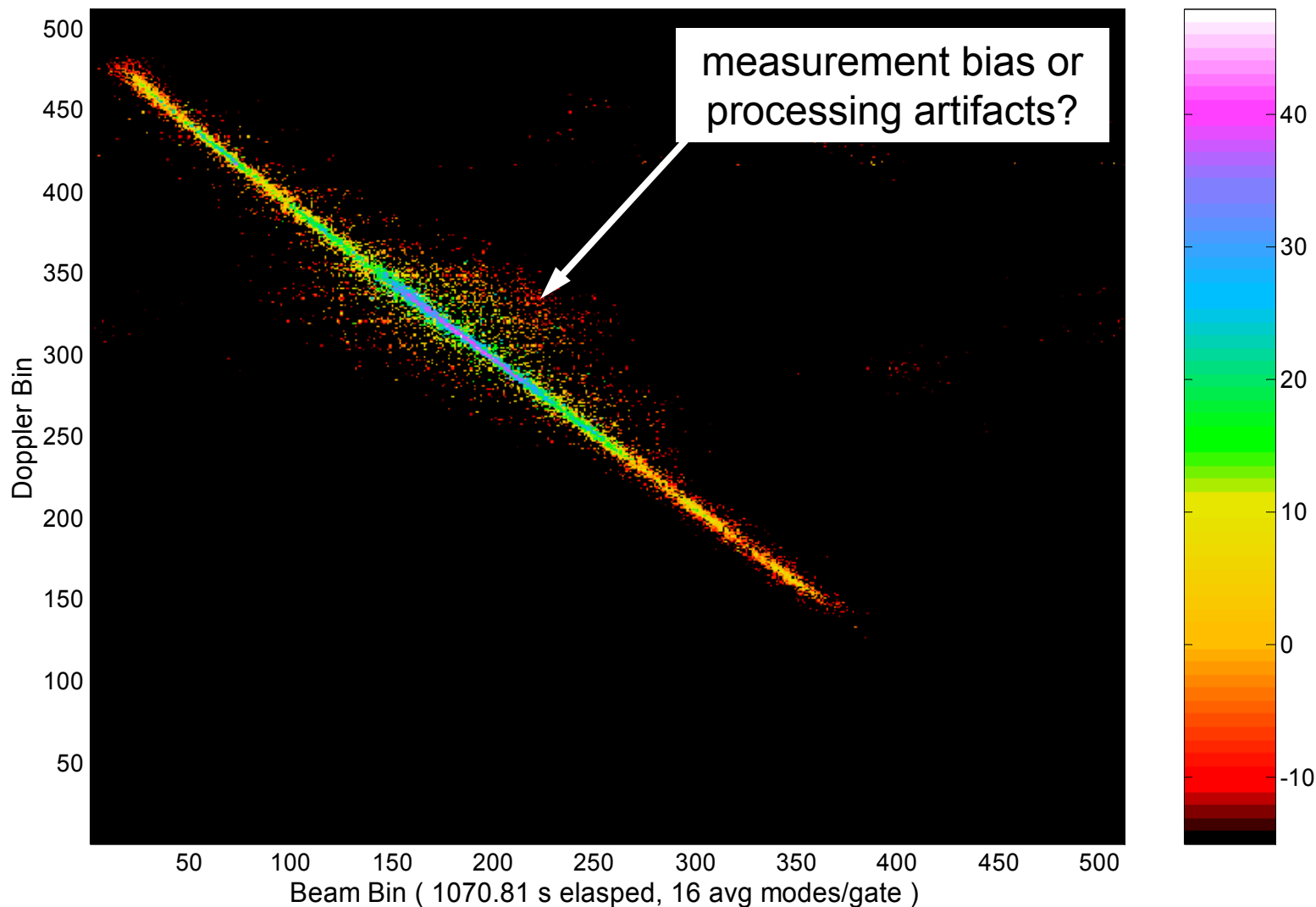


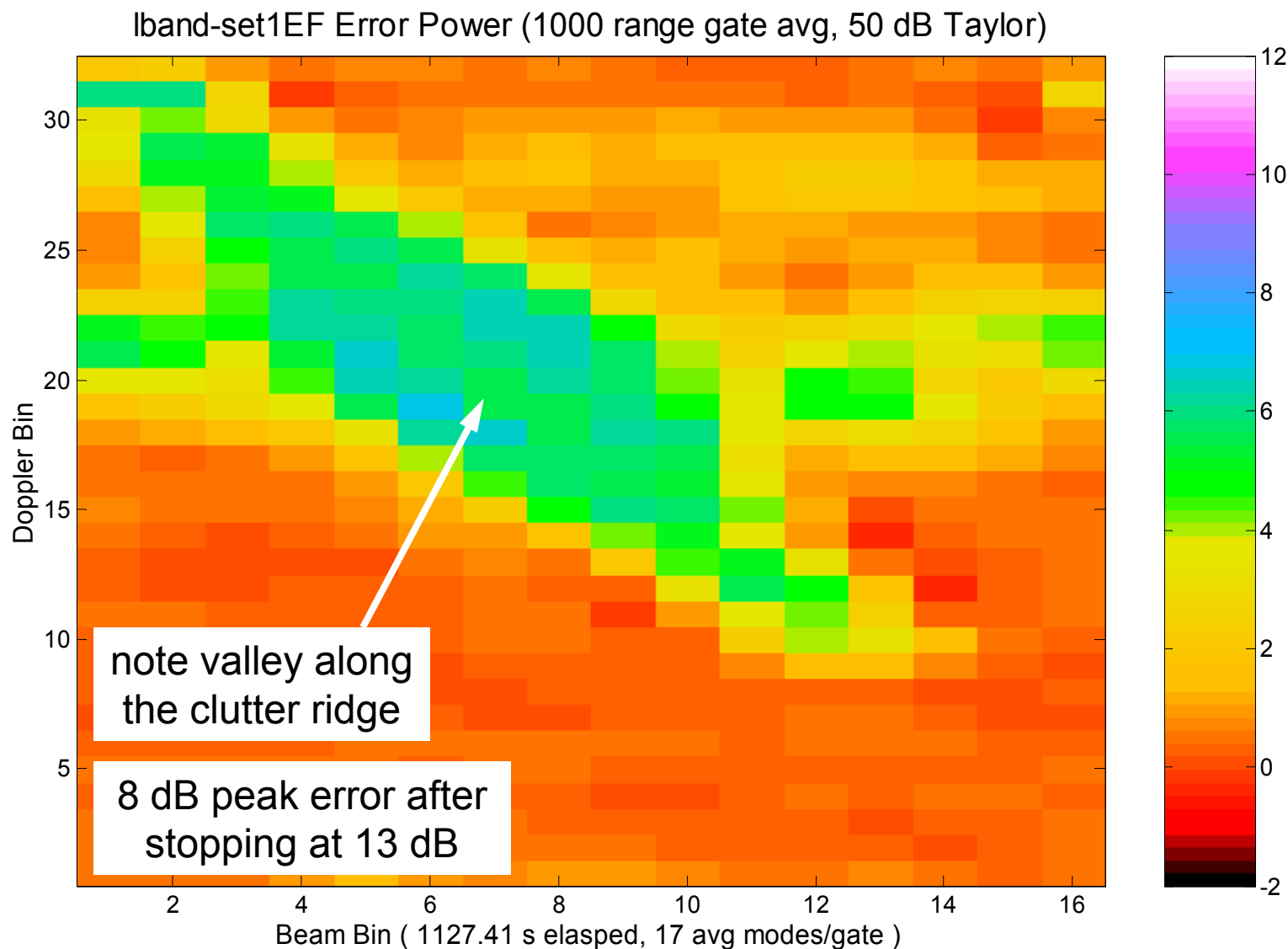


Focused Nonlinear Estimate Range-Averaged Target-Only "Power"

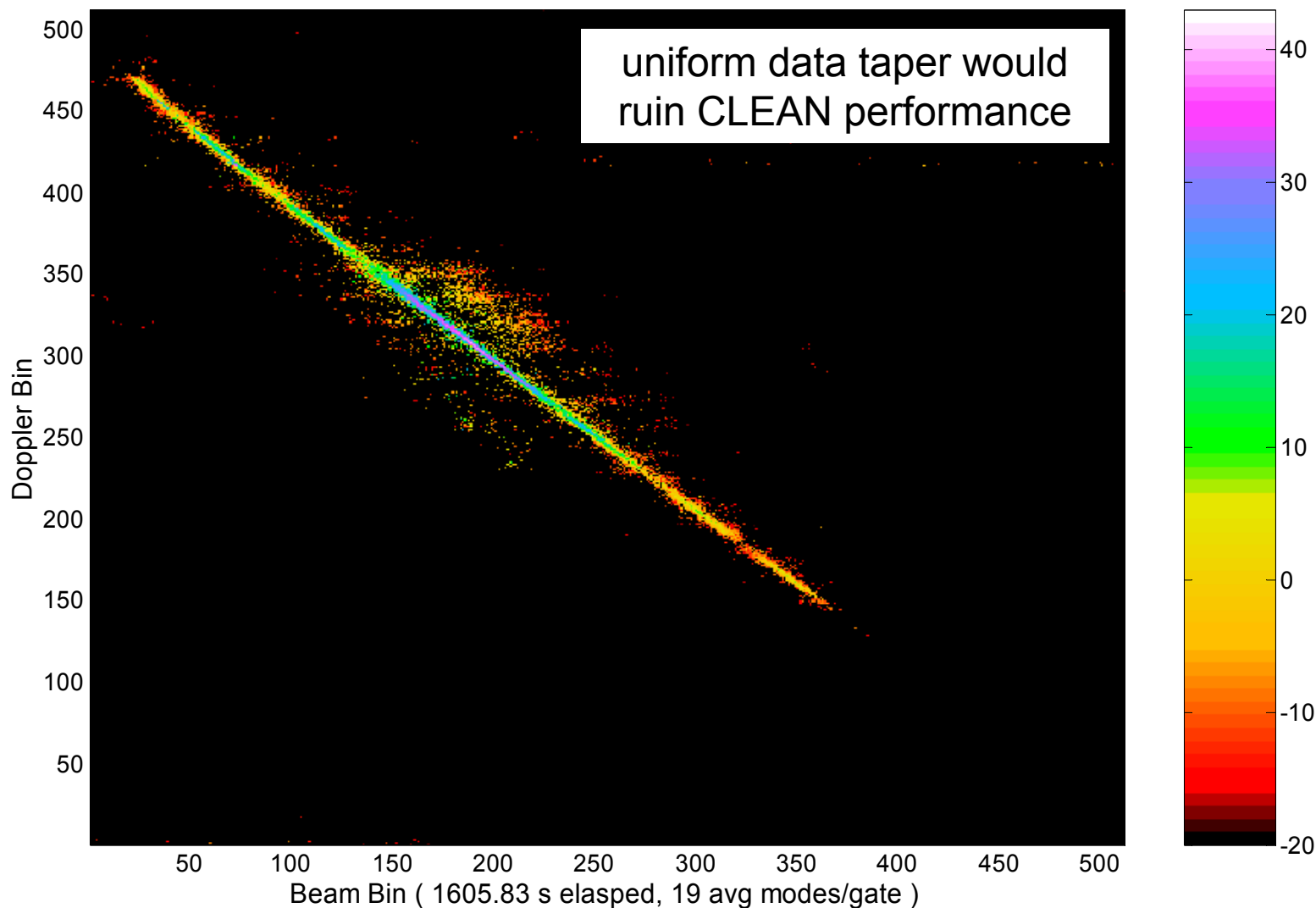


iband_set1_ngmEFX-1-512 Scatterer Power (1000 range gate avg, 50 dB Taylor)





lband-set1EFX-1-512 Scatterer Power (1000 range gate avg, uniform)





Some Questions Raised by Latest SCHISM Results

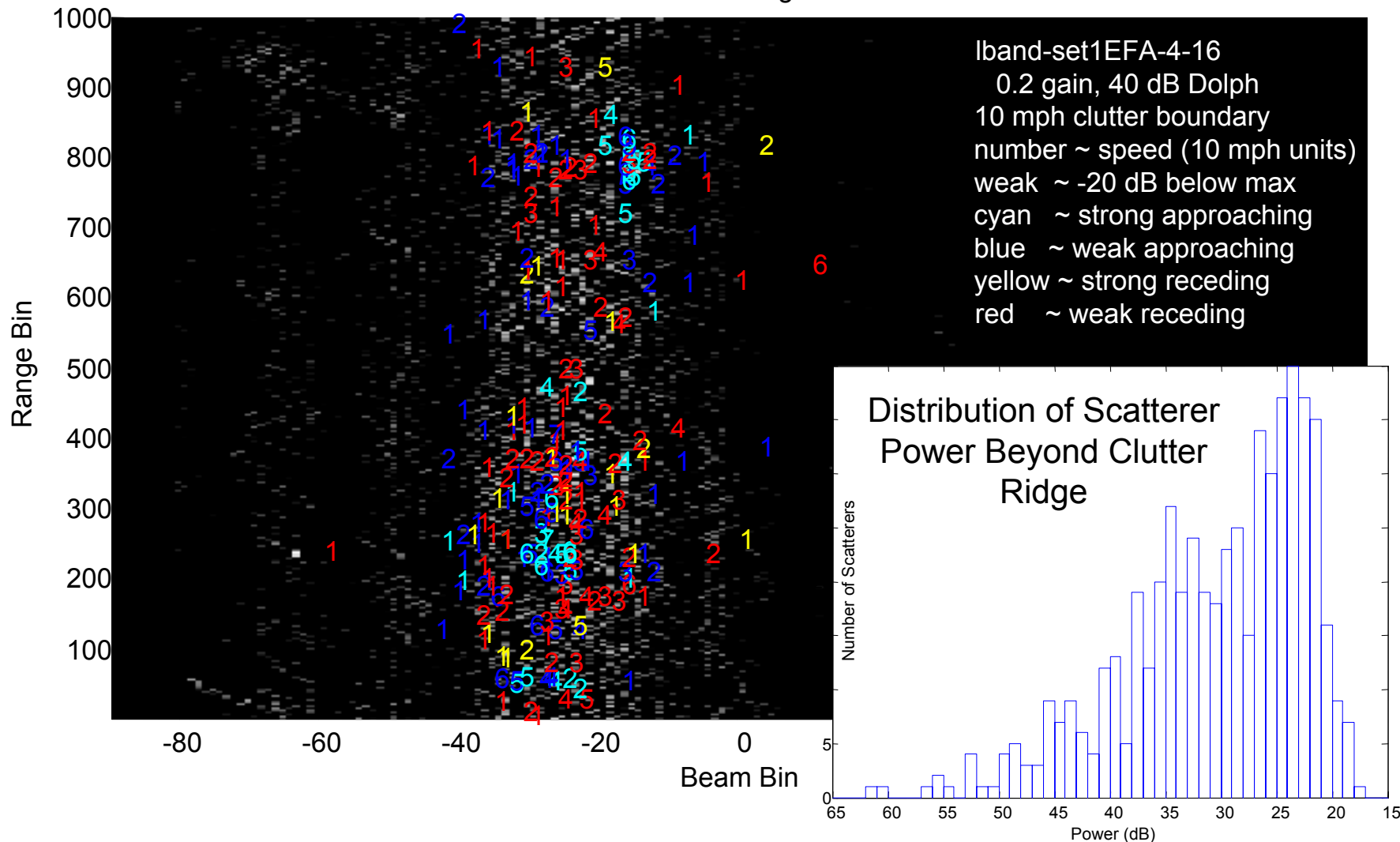


- False clutter: How severe? Caused by uncorrected measurement biases?
 - Do analysis procedures yielding fewer modes produce “better” results?
 - Are targets preserved by analysis procedures (S/N stopping point)?
 - How can analysis procedures reduce false alarms (precision vs accuracy)?
 - Is recursive high-order cal-on-clutter over successive range bins feasible?
 - Can several CPIs be coherently merged using clutter for alignment?
 - Is there an efficient (hopefully systolic) architecture for SCHISM?
 - Will SCHISM work on a genuine datacube?
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Next Steps

- Scrutinize mode analysis for ideal non-clutter and non-target datacubes.
- Synthesize ideal target mode distribution in beam-Doppler for comparison.

30 dB Threshold Yields 250 "Targets" Faster Than 10 MPH

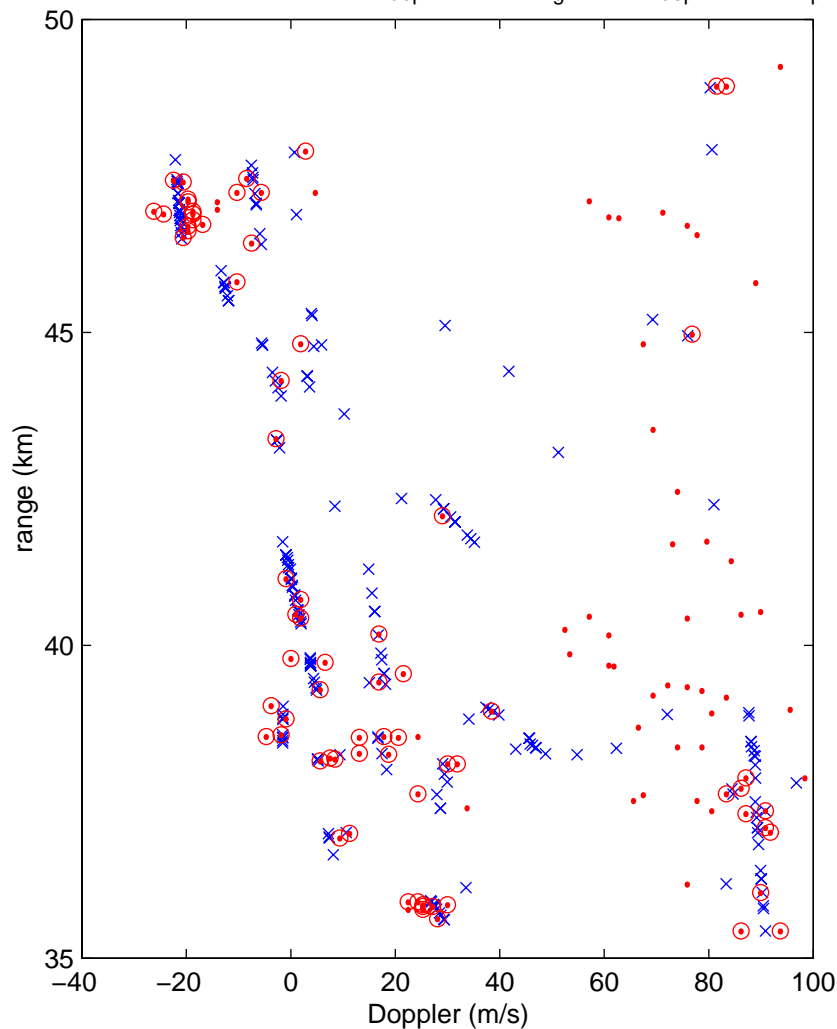




(Old) All SCHISM Detections > 10 m/s (Bergin, ISL)



associations: 77, false alarms: 45, Δ_{dop} : 5 m/s, Δ_{rng} : 40 m, t_{dop} : 10 m/s, t_{pwr} : 50 dB



- **Power threshold = 50dB**
- **Range-rate threshold = 10 m/s**

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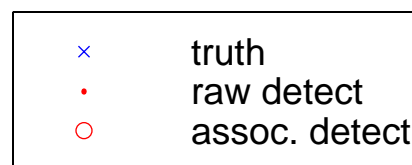
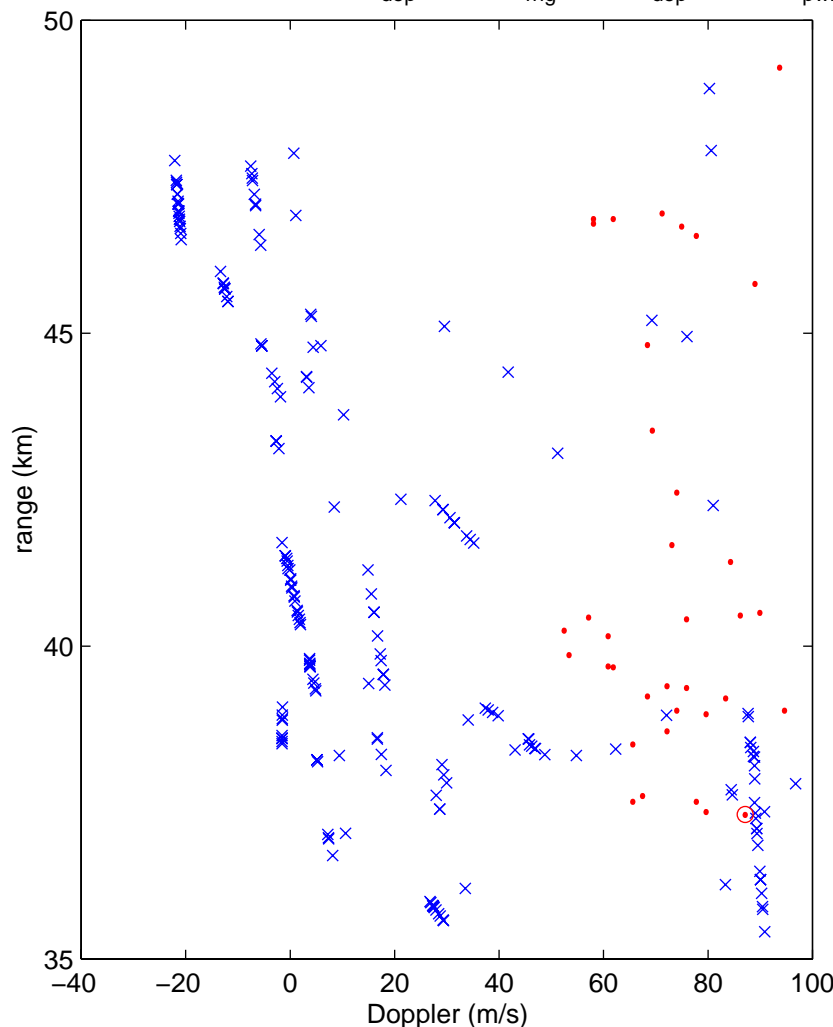




(Old) All SCHISM Detections > 10 m/s targetless datacube (Bergin, ISL)



associations: 1, false alarms: 35, Δ_{dop} : 5 m/s, Δ_{rng} : 40 m, t_{dop} : 10 m/s, t_{pwr} : 50 dB



- No ground movers in the data
- Power threshold = 50dB
- Range-rate threshold = 10 m/s

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